Exoplanet Exploration Program Update

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NASA Exoplanet Exploration Program

Jet Propulsion Laboratory

California Institute of Technology

CL# URS266563

June 18, 2017

ExoPAG #16

Mountain View, California

Artist concept of Kepler-16b .
Credit: NASA/JPL-Caltech/T. Pyle

Program Overview

Program Updates

Science Highlights

What’s Coming Up

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

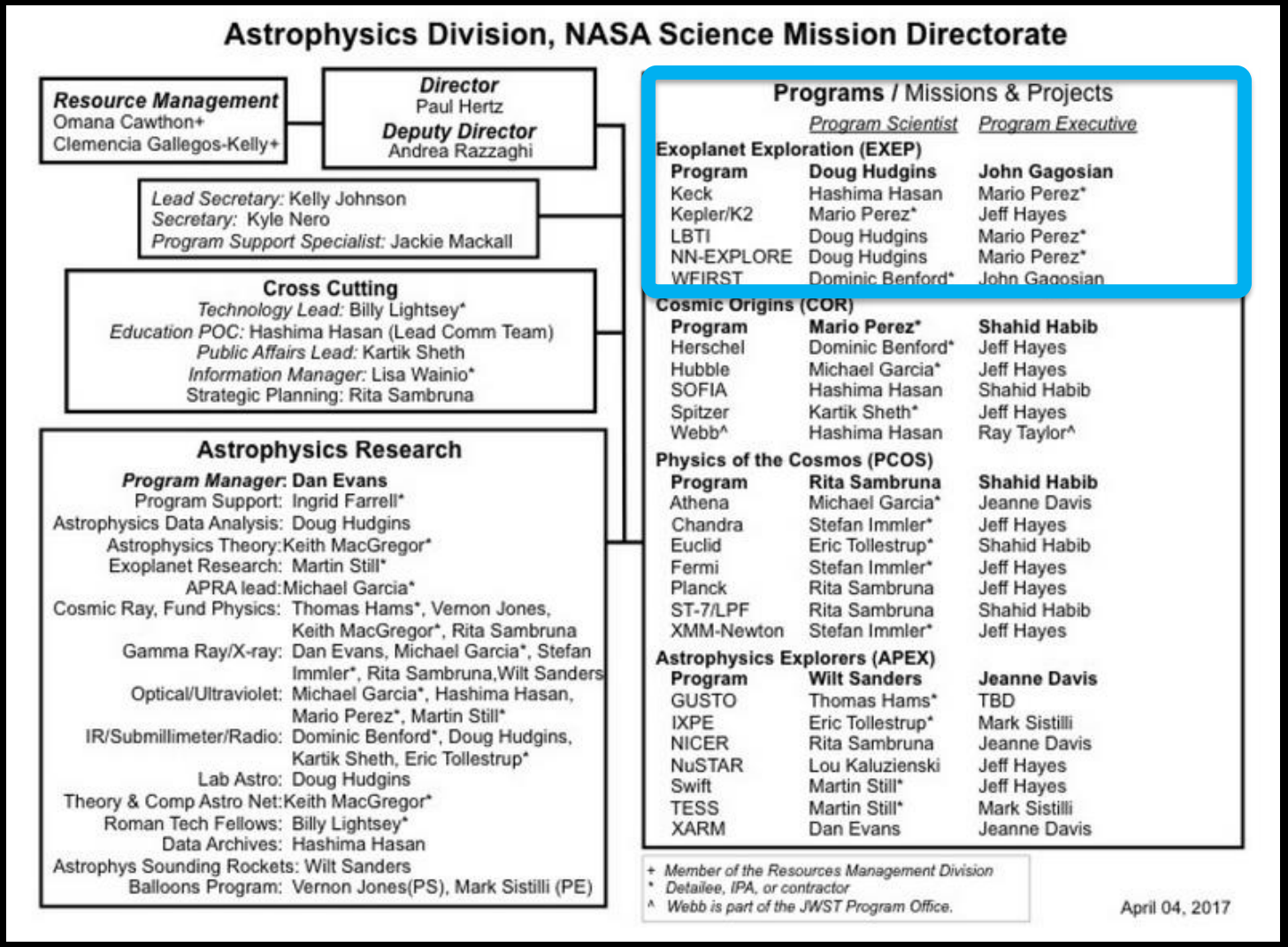
Program purpose described in **2014 NASA Science Plan**

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

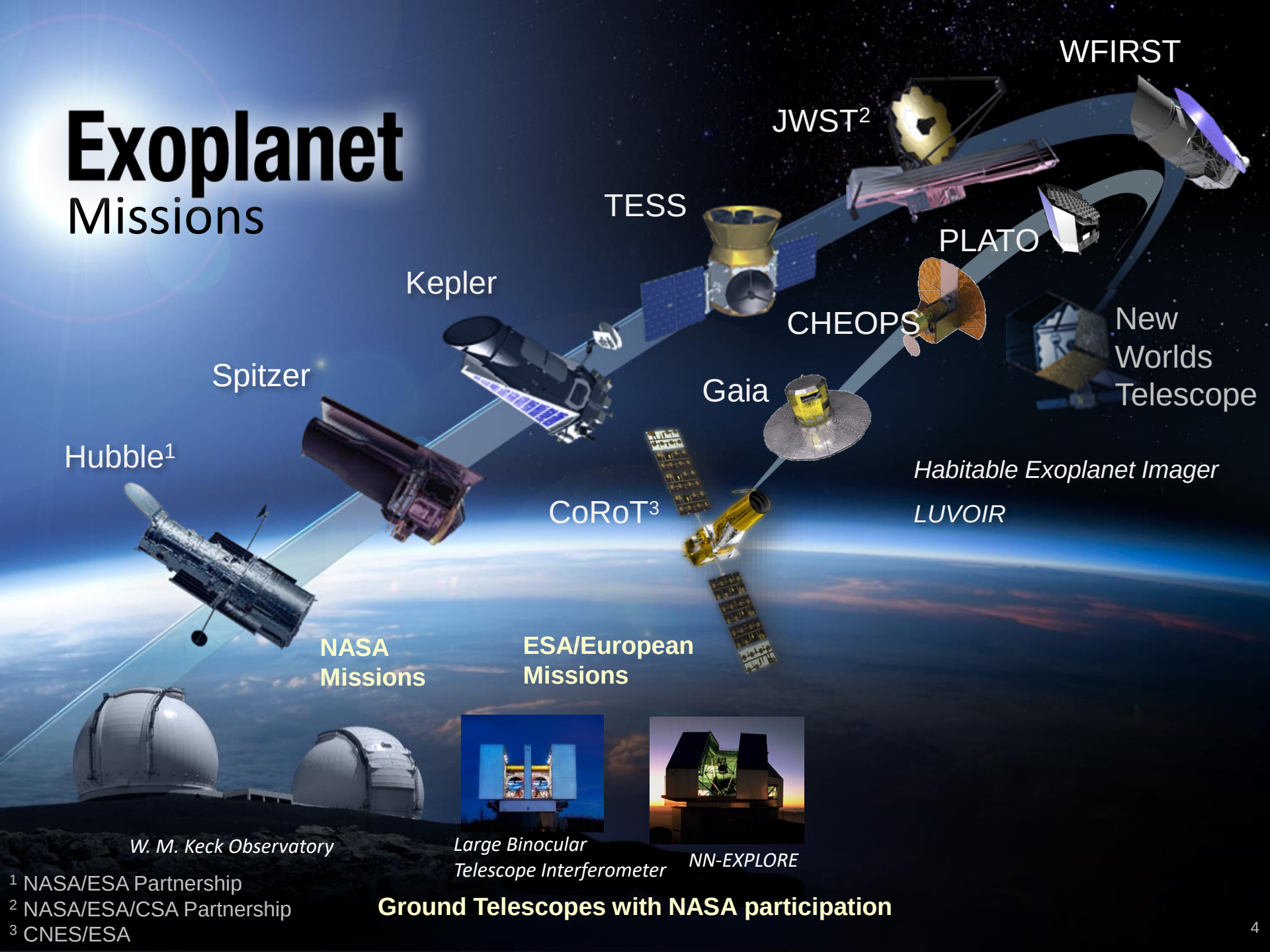
ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov

ExEP is a Program Office within the NASA Astrophysics Division



Exoplanet Missions



[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

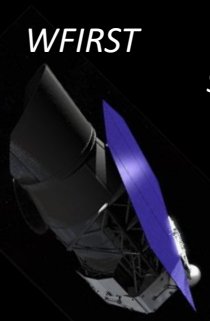
Ground Telescopes with NASA participation

NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2

WFIRST



Starshade

Decadal Studies

Coronagraph

Communications

Supporting Research & Technology

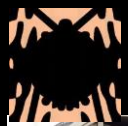
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

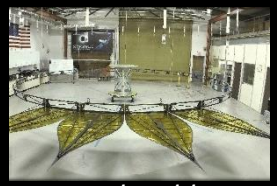
NN-EXPLORE

Technology Development



Coronagraph Masks

High-Contrast Imaging



Deployable Starshades

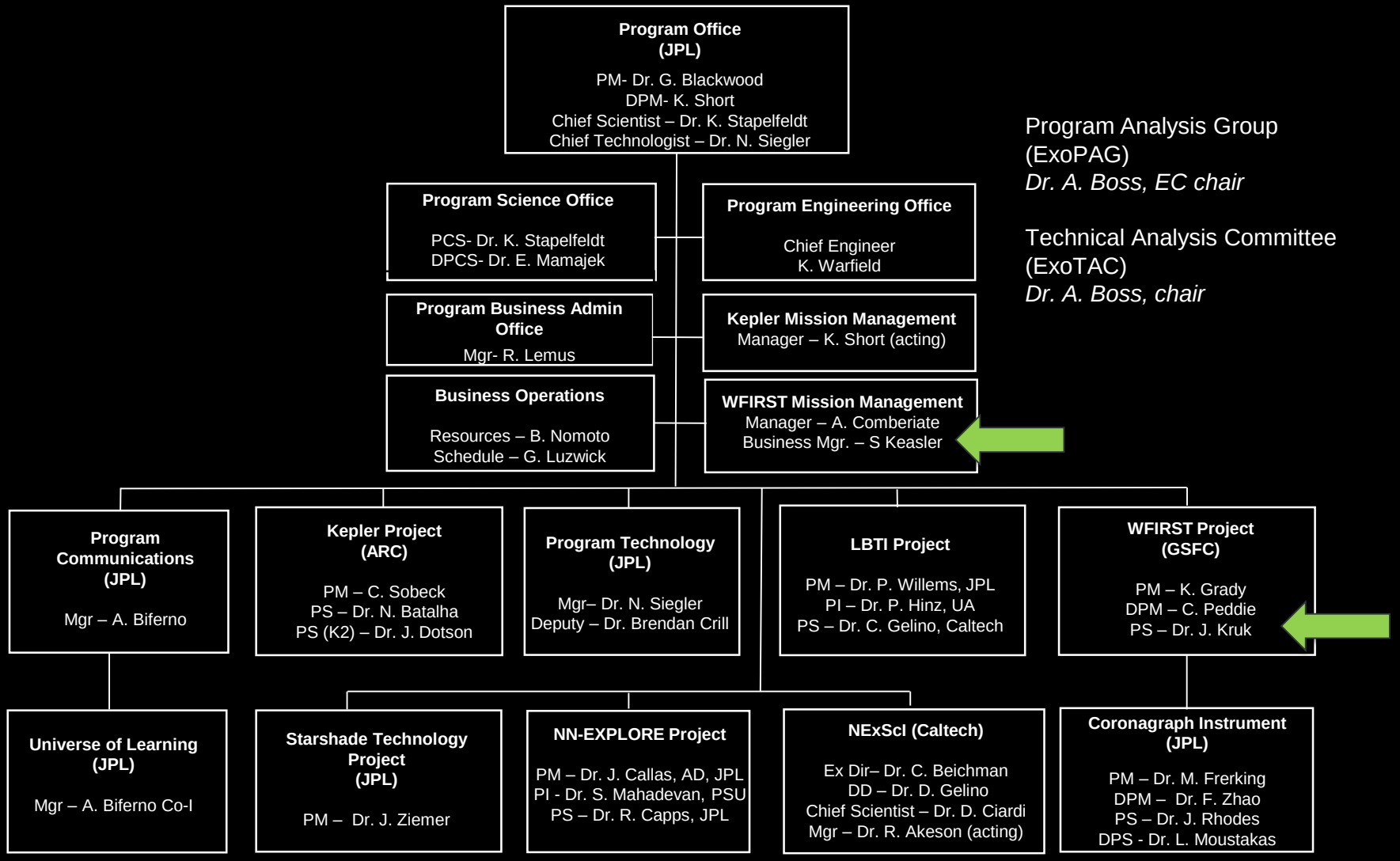
NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate



Program Analysis Group (ExoPAG)
Dr. A. Boss, EC chair

Technical Analysis Committee (ExoTAC)
Dr. A. Boss, chair

Exoplanet Exploration Program

Enables Science Today and Tomorrow

Scope: Projects and Tasks

Purpose

Legend: • Projects • Tasks • *Science*	Today	*Enabled Science*	Future	*Enabled Science*
Discover	• Kepler • K2	• *Occurrence rates for science and design of future missions* • *Discoveries via photometry and microlensing, potential JWST Targets*	• WFIRST Microlensing Survey	• *Census for long period planets*
Characterize	• NASA Keck time • NNEXPLORE GO, including NESSI • NASA Exoplanet Archive	• *SMD Science, Exoplanet follow up and precursor science* • *Transit prediction and observability for space missions* • *Table of transmission spectroscopy data including from HST and Spitzer.*	• NEID GO • WFIRST Coronagraph • Original Probe Studies (Coronagraph, Starshade) • OST	• *Exoplanet Mass* • *Reflected Light Spectroscopy of Atmospheres*
Space Missions Not in the ExEP	• HST • Spitzer	• *Atmospheres, microlensing discoveries*	• TESS • JWST	• *Photometry, atmospheres via transmission spectroscopy*
Identify Worlds that Could Harbor Life	• Large Binocular Telescope Interferometer • Technology - Competed • Starshade Technology Development • Starshade Readiness Working Group • Segmented Coronagraph Design and Analysis • Telescope Stability Workshop	• *Exozodiacal Dust survey* • *Increasing TRL feasibility* • *Decreasing inner working angle* • *Increasing outer working angle* • *Increasing starshade suppression* • *Minimizing segmented mirror edge diffraction* • *Increasing coronagraph contrast*	• Current Probe Starshade - WFIRST Rendezvous (Seager, Kasdin) • LUVOIR • HabEx • OST • Current Probe Precision RV in Space (Plavchan) • Standard Definitions and Evaluation Team	• *Reflected Light Spectroscopy of Atmospheres* • *Reflected Light, Transmission Spectroscopy* • *Mass Measurements*

Wide Field Infrared Survey Telescope (WFIRST)

Dark Energy, Infrared Survey… and Alien Worlds

- WFIRST in Phase A
- All technology milestones were met on time
  - Five for IR Detector, now at TRL 6
  - Nine for Coronagraph, now at TRL 5
- Actively studying making WFIRST starshade-ready.
- Reviews for SRR/MDR: delayed to allow independent external review
- https://www.nasa.gov/feature/nasa-taking-a-fresh-look-at-next-generation-space-telescope-plans

Credit: NASA/GSFC

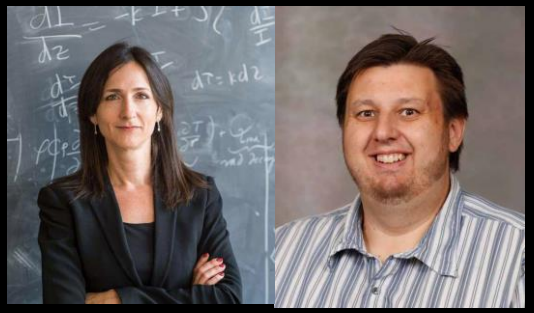
Astrophysics Probe Mission Concepts

Announced by NASA March 20

PI	Affiliation	Title
Camp, J.	NASA's Goddard Space Flight Center	Transient Astrophysics Probe Concept Study
Cooray, A.	Univ. California, Irvine	Cosmic Dawn Intensity Mapper
Danchi, W.	NASA's Goddard Space Flight Center	Cosmic Evolution through UV spectroscopy (CETUS)
Glenn, J.	Univ. of Colorado	Galaxy Evolution Probe
Hanany, S.	Univ. of Minnesota	Inflation Probe Mission Concept Study
Mushotzky, R.	Univ. of Maryland	AXIS: A High Spatial Resolution X-ray Probe Satellite
Olinto, A.	Univ. of Chicago	Concept Study of the Probe Of Extreme Multi Messenger Astrophysics (POEMMA)
Plavchan, P.	Missouri State Univ.	EarthFinder: A Diffraction-Limited Precise Radial Velocity Observatory in Space (*Partial selection)*
Ray, P.	Naval Research Laboratory	STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years
Seager, S.	Massachusetts Institute of Technology	Starshade Rendezvous (*Partial selection)*

- 10 proposals selected for mission concept studies
  - PI-led science team
  - NASA mission design labs at JPL and GSFC.
  - Results will be provided to 2020 Decadal Committee

- 2 exoplanet studies were "partially" selected:
  - Peter Plavchan: develop the science case for space PRV mission.
  - Sara Seager: update starshade rendezvous mission concept.



- The ExEP and PCOS / COR programs are facilitating all ten studies by supporting the PIs throughout the study and more specifically assisting the PIs in executing their design lab studies.

TEAMX Jet Propulsion Laboratory

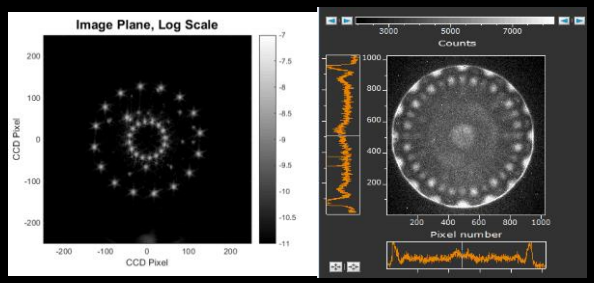
Goddard Space Flight Center Integrated Design Center

Starshade Technology Development (S5)

- Held two workshops on scattered sunlight from edges and the mechanical architecture trade space
  - Per plan, one more workshop to go on starlight suppression demonstration
  - Adding a new workshop on petal shape and science return
- Key Technology Achievements
  - Demonstrated starlight suppression modeling agreement within 10%
  - Princeton starlight suppression demonstration currently at $10^{-7.5}$ (mask limits)
  - Demonstrated half-scale deployment of inner disk optical shield
  - Developed sensing algorithms for formation flying using WFIRST CGI constraints

Starshade Workshops

Contrast at higher Fresnel number, exposure time: 100s



Suppression at flight Fresnel number, exposure time: 3000s

Inner optical shield deployment tests

NN-EXPLORE

Partnership for Exoplanet Discovery and Characterization

- Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope
  - Laser frequency comb reference
- Development milestones:
  - Passed the Instrument Detailed Design Review in November 2016
  - Passed the Port Adapter Detailed Design review in May 2017
  - Instrument commissioning by August 2019
- Ongoing Guest Observer program using 40% NOAO share of telescope time for exoplanet research with existing instruments. Proposals due in late September.
- See John Callas' talk in Wed. splinter session

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

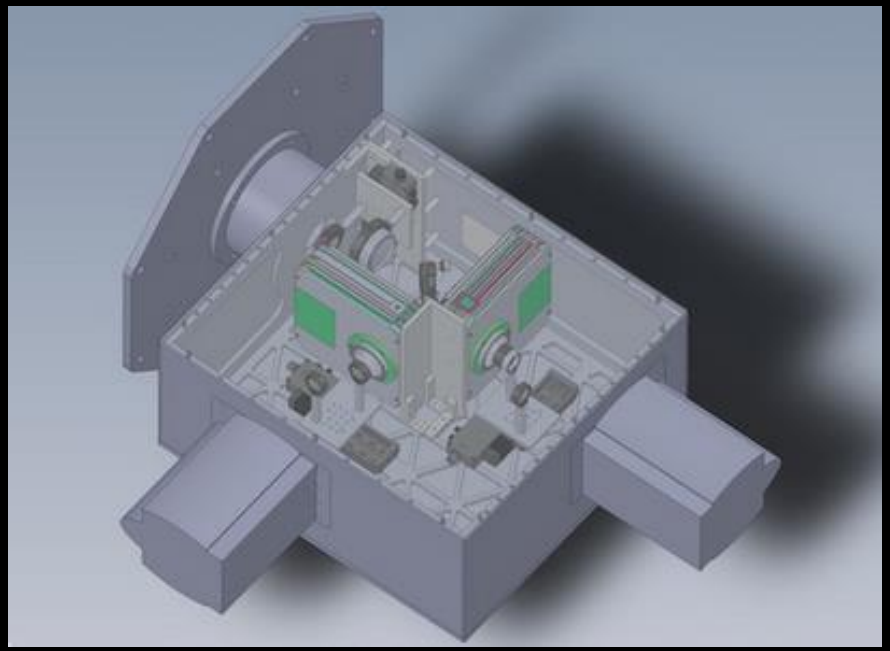
PI: S. Mahadevan

NOAO 3.5-m WIYN Telescope, Kitt Peak National Observatory, Arizona

NESSI on WIYN 3.5m Observatory, Kitt Peak

The NASA Exoplanet Star (and) Speckle Imager

- Speckle images in two simultaneous colors
- Resolution at or near diffraction limit
- Companion detection and characterization to delta magnitudes of ~5
- PI: Steve Howell, NASA ARC



http://www.wiyn.org/Instruments/

Sagan Fellowship Program

Training the next generation of exoplanet scientists

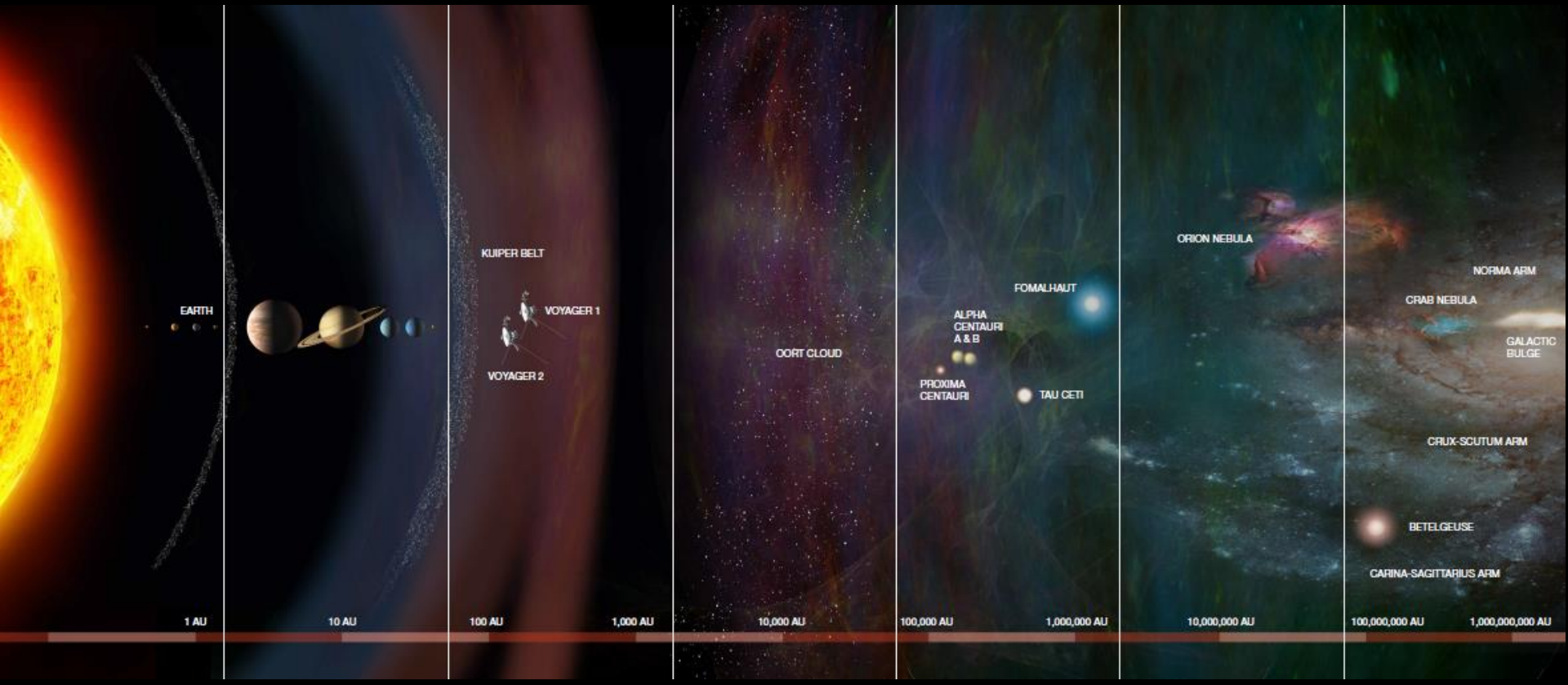
Raphaëlle Haywood
Harvard
Breaking the Ultimate Barrier to Characterizing Other Earths

Ben Pope
NYU
Finding Planets Around Naked-Eye Stars

Andrew Vanderburg,
University of Texas, Austin
The Galactic Distribution of Exoplanets

Exoplanet Communications

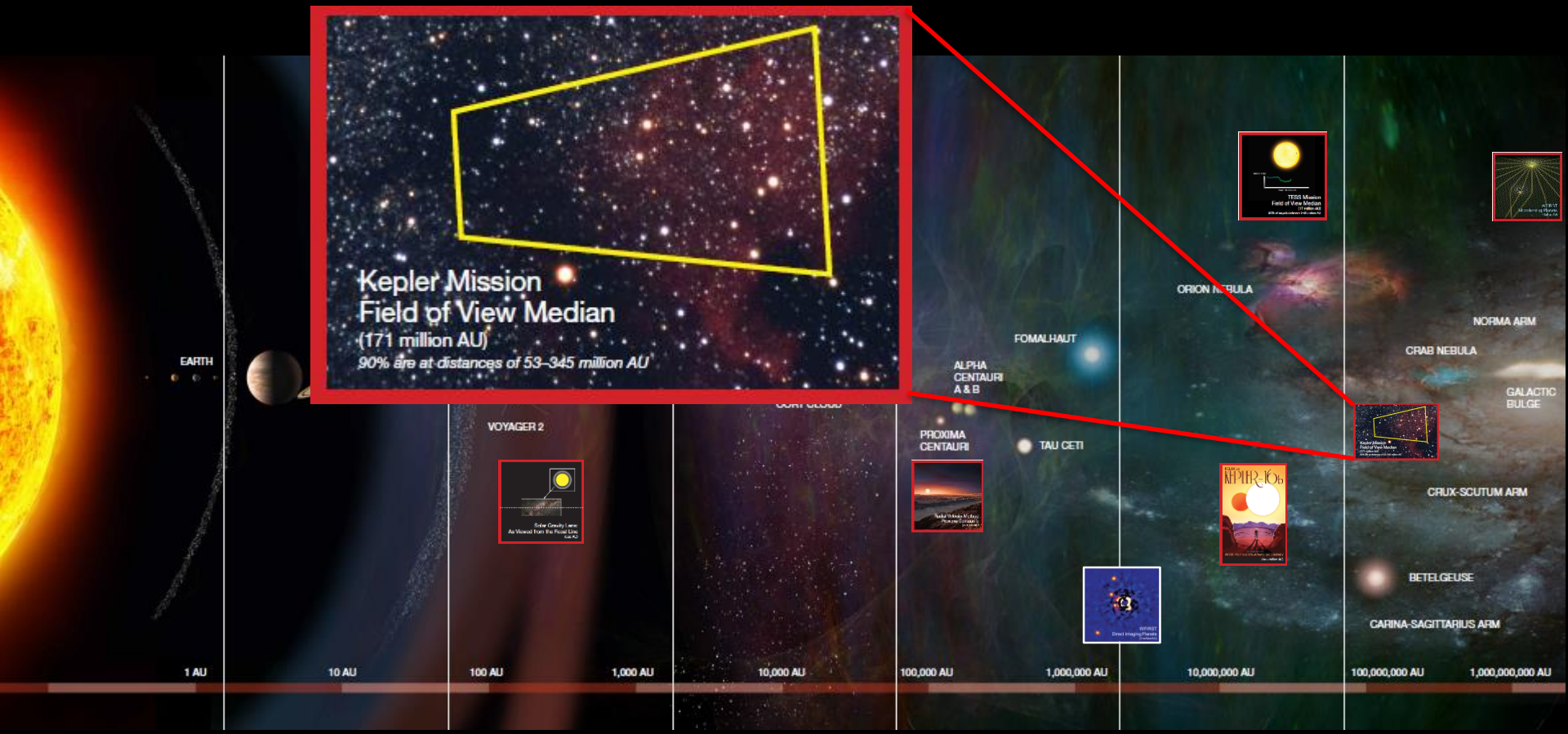
Interstellar Visual Display Exhibit



1 AU 100 10,000 E6 1E9 AU

Exoplanet Communications

Interstellar Visual Display Exhibit



1 AU 100 10,000 E6 1E9 AU

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Exoplanet Exploration Program Science Plan

- Covers roles and processes for the ExEP Science Office.
- The Plan also contains the scientific and programmatic context for the Program Science Gap list.
- Aligned with strategy & goals of the 2014 NASA Science Plan and community reports
- The Science Gap List would be included as an appendix to the Science Plan, similar to the ExEP Technology Plan, and provide an opportunity to align work across the agency with Program goals
- Jointly authored by Stapelfeldt & Mamajek. First draft to be completed later this month

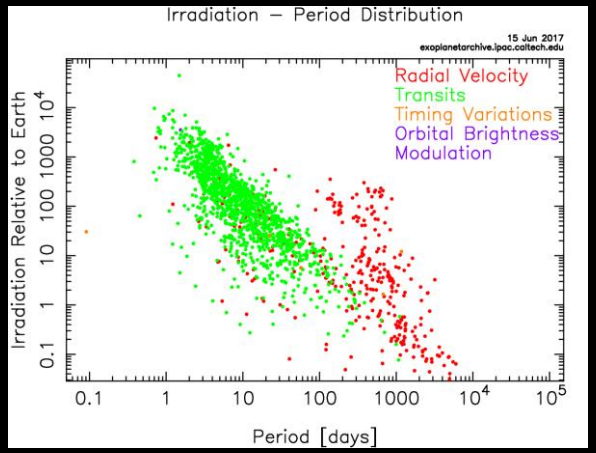
Some Exoplanet Science gaps within current community priorities:

- Achieving RV sensitivity to Earth-like planets: mitigating RV jitter
- Exozodi as a noise source for flagship imaging
- Community RV facilities for Kepler, K2, TESS followup
- Dedicated WFIRST/CGI RV precursor program
- Final Kepler occurrence rates for small planets
- Quantified science yield comparison between Flagships, probes, and WFIRST
- Combining exoplanet demographics from multiple methods
- Generation of Lightcurves for TESS Full Frame Images* (external to ExEP)

NASA Exoplanet Science Institute

NASA Exoplanet Science Institute
California Institute of Technology
NExScI

- Sagan Summer Schools
- Sagan Fellowship Program
  (new role working with STScI)
- NASA/Keck time (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science
- Exoplanet Archive tracks exoplanet population and Kepler pipeline products
- Exoplanet Follow-up Observing Program supports Kepler & K2 sources follow-up



Large Binocular Telescope Interferometer

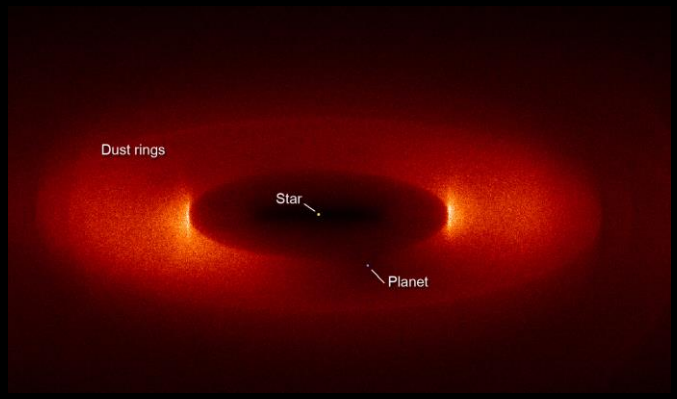
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

Credit: ESO/Y. Beletsky

- 35-star survey, September 2018
- Progress: 26 stars observed
- Measurement Precision: ~12 zodi, one star one sigma
- See Steve Ertel's talk at 2pm today

Phil Hinz, PI

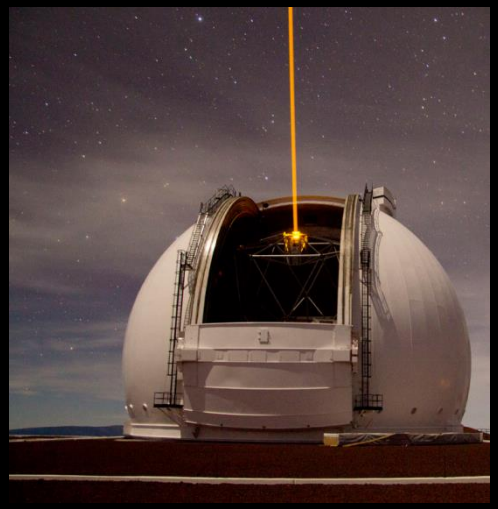
THE UNIVERSITY OF ARIZONA



Credit: NASA/GSFC

Ground-Based Support for Space Missions

Partnering to Enable Key Projects for Strategic Reasons



Keck Observatory: (1/6 partner)
Key SMD Project and GO Investigations

Large Binocular Telescope Interferometer:
Exozodiacal Dust Survey
University of Arizona

NN-EXPLORE deploying WIYN Telescope
NEID Precision Radial Velocity Instrument

NASA Keck Time Administration

2018A Observing Opportunities

- NExScI solicits science and mission support proposals for NASA's portion of the time on the two 10m WM Keck telescopes
- All proposals for the 2018A Semester are due September 14, 2017
  - Key Strategic Mission (KSMS) Support Proposals will be solicited in this semester to support missions in astrophysics and planetary science. 10-60 nights spread over up to 3 years
  - *Precursor science or early follow-up for TESS and JWST will only be able to propose to KSMS in 2019B or for general Mission Support in 2018A*
  - Non-binding letter of intent due August 16 for KSMS proposals

- PIs must be based at a U.S. institution
- Contingent upon funding, accepted proposals may receive limited funding

Kepler Close-Out

Delivering Kepler's Legacy

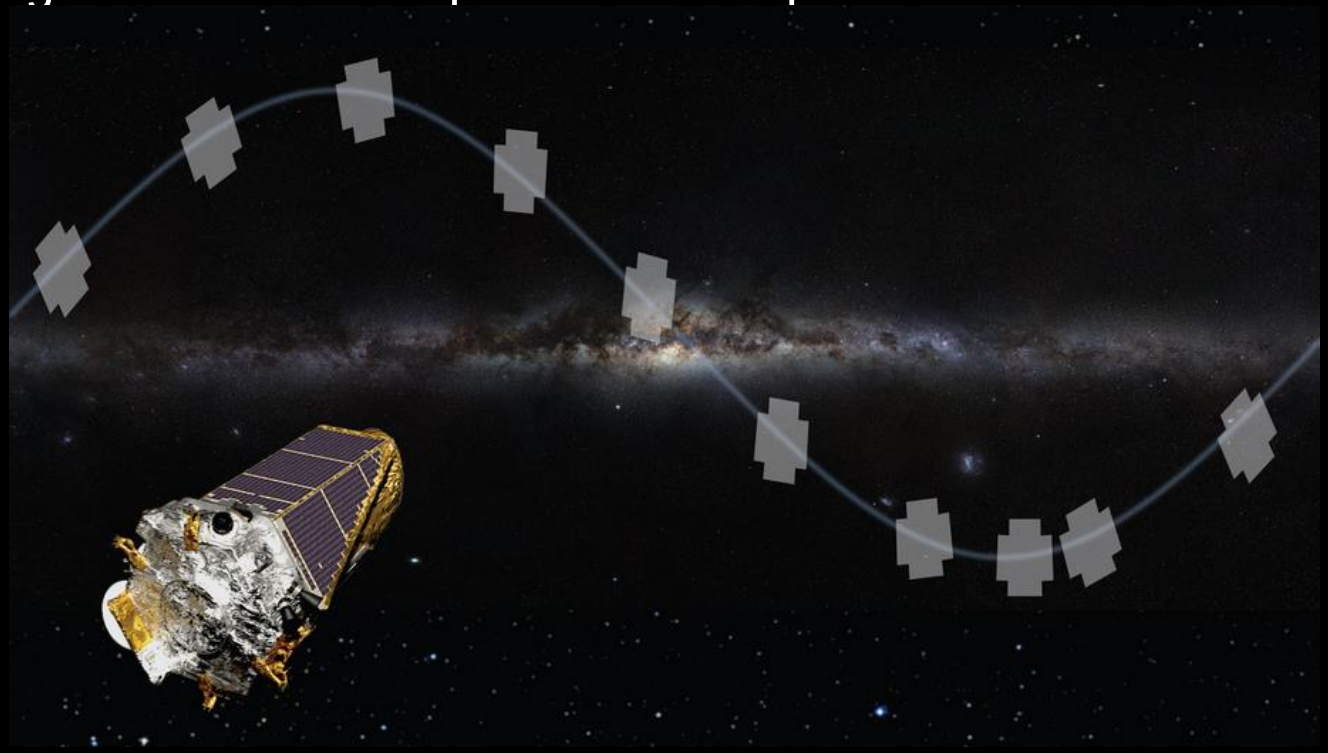
- Kepler SOC9.3 Final Catalog and Occurrence Rate data has been delivered and is live at the NExScI Data Archive.

- Kepler closeout and final data processing continues steadily within overall schedule margin

Credit: NASA/ARC

Kepler / K2

Extending the Power of Kepler to the Ecliptic



Recently completed Campaign 13 (Taurus); now in Campaign 14 (Leo)

Upcoming:

- Changed the position of the field for Campaign 16 – Kepler will observe in the forward-facing direction; emphasis on supernova science
- Campaign 17, 18, 19 fields have now been selected

https://exoplanets.nasa.gov/k2

Discovery of Trappist-1 system had big public impact

"All the News That's Fit to Print"

The New York Times

Late Edition
Today, patchy morning fog, partly sunny, warm, high 64. Tonight, mostly cloudy, mild, low 52. Tomorrow, clouds and sunshine, showers, high 66. Weather map is on Page B9.

VOL. CLXVI ... No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017 $2.50

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

TRUMP RESCINDS OBAMA DIRECTIVE ON BATHROOM USE

ENTERING CULTURE WARS

Question of Transgender Rights Splits DeVos and Sessions

This article is by Jeremy W. Peters, Jo Becker and Julie Hirschfeld Davis.

WASHINGTON — President Trump on Wednesday rescinded protections for transgender students that had allowed them to use bathrooms corresponding with their gender identity, overruling his own education secretary and placing his administration firmly in the middle of the culture wars that many Republicans have tried to leave behind.

In a joint letter, the top civil rights officials from the Justice Department and the Education Department rejected the Obama administration's position that nondiscrimination laws require schools to allow transgender students to use the bathrooms of their choice.

That directive, they said, was improperly and arbitrarily devised, "without due regard for the primary role of the states and local school districts in establishing

Circling a Star Not Far Away, 7 Shots at Life

By KENNETH CHANG

Uber's Culture Of Gutsiness Under Review

By MIKE ISAAC

Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

No going to church, no going to the store. No doctor's appointments for some, no school for others. No driving, period — not

IMMIGRATION A police department worries a crackdown will harm work to fight gangs. PAGE A14

MEXICO The secretary of state pays a visit at a time of rising

duras.

If deportation has always been a threat on paper for the 11 million people living in the country illegally, it rarely imperiled those who did not commit serious crimes. But with the Trump ad-

ARTS: LOOK INSIDE FOR OUR OSCARS RECAP PAGE 4

THE DAILY CALIFORNIAN

BERKELEY'S NEWSPAPER SINCE 1871 BERKELEY, CA • MONDAY, FEBRUARY 27, 2017 WINNER OF THE 2016 ONLINE PACEMAKER

RESEARCH & IDEAS

Campus reacts to TRAPPIST-1

NASA, TRAPPIST telescope discover 7 planets with potential to harbor life

BY ELLA JENSEN | STAFF
EJENSEN@DAILYCAL.ORG

NASA confirmed the existence of five more Earth-like planets Wednesday after Belgium-operated telescope TRAPPIST discovered two in 2016, providing astronomers with the first concrete opportunity to search for intelligent life outside of the solar system.

UC Berkeley astronomers from the Berkeley Search for Extraterrestrial Intelligence (SETI) Research Center are also searching for planets that may contain intelligent life. According to campus astronomy professor Alex Filippenko, the Automated Planet Finder telescope located at the university-owned Lick Observatory has observed a few new planets in the past, but none quite as "amazing" as the seven recently discovered planets.

The seven planets are located at about the right distance from their host star TRAPPIST-1 to have the same temperature as Earth, making the existence of water on their surfaces a possibility, according to a study published Thursday in the scientific journal Nature. TRAPPIST-1 is 40 light years, or about 235 million miles, from Earth, according to NASA. Scientists have classified it an "ultra-cool dwarf" star, meaning that it is cool and relatively small in size — only 4,150 degrees Fahrenheit compared to Earth's approximately 10,000-degree sun. It has about eight percent of the mass of the sun and its dim radiance makes observing it with a telescope much easier.

NASA's James Webb Space Telescope, set to launch in 2018, could provide astronomers with additional data regarding the amount of water, methane and oxygen in TRAPPIST-1's atmosphere.

The Breakthrough Listen Initiative, a scientific search for extraterrestrial life, is working within SETI to make astronomical data available to the public.

"The study released is a great interest to us because many of the best places to look for life are on planets where the conditions might be right for life," said Steve Croft, campus astronomer and a member of the Breakthrough Listen Initiative.

According to Andrew Siemion, director of SETI and the Breakthrough Listen Initiative, SETI looks for "artifacts of intelligence" on foreign planets in various forms because there is no way to detect life at interstellar distances using the direct methods that researchers might use to explore life on Earth.

"We are attempting to answer what we believe to be humanity's oldest and most profound question," Siemion said.

PLANETS PAGE 2

TRAPPIST-1 AND ITS SEVEN PLANETS

Orbital period = unknown
Orbital period = 12.35 days
Orbital period = 9.1 days
Orbital period = 6.06 days
Orbital period = 4.04 days
Orbital period = 2.42 days
Orbital period = 1.51 days

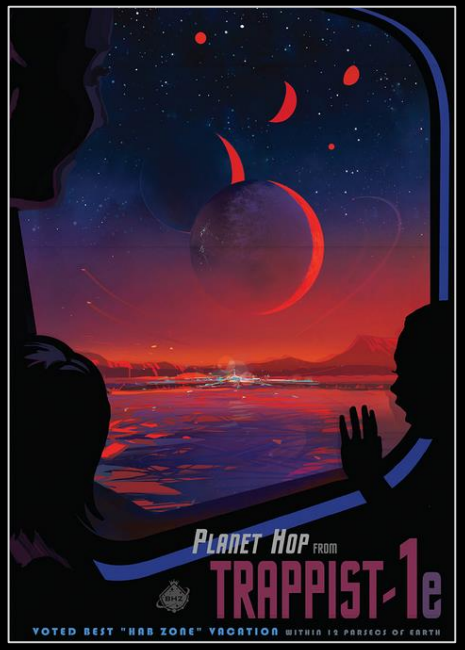
TRAPPIST-1
• Red star
• Approximately the size of Jupiter

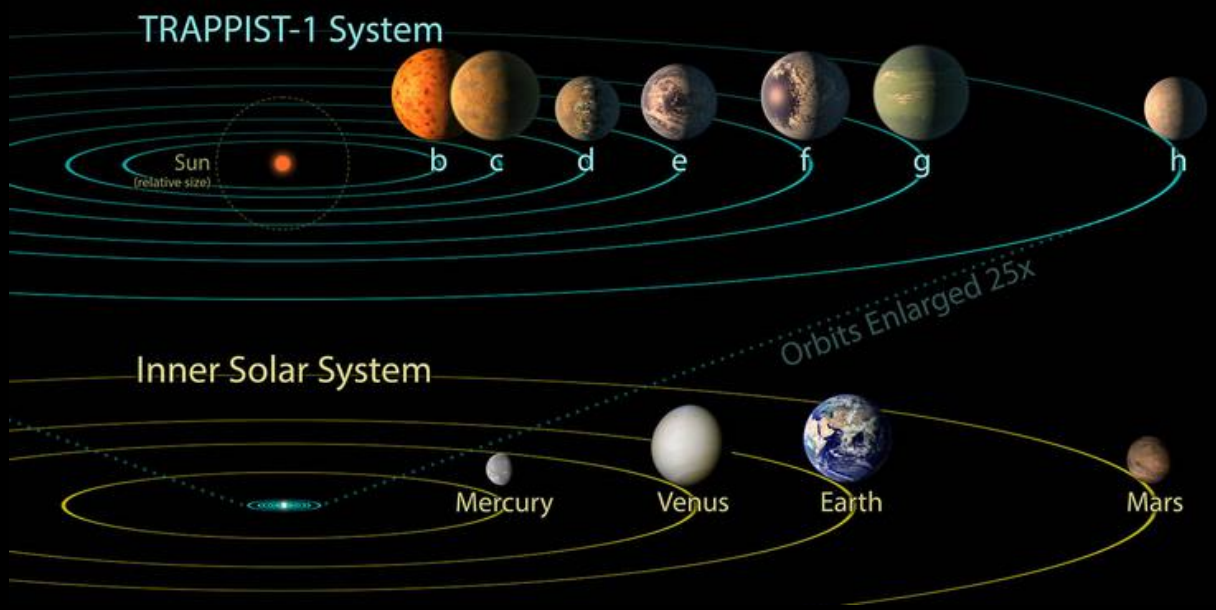
What we know:
• The star and its planets are located about 12 parsecs away from the solar system
• All seven planets have equilibrium temperatures low enough to make the existence of liquid water on their surfaces a possibility
• All seven planets have sizes and masses similar to those of Earth.

7 Earth-sized exoplanets, at least 3 of which lie in the habitable zone where liquid water is possible, were found by the transit method orbiting an ultra-cool dwarf star

Trappist-1 Discovery

The Richest Set of Earth-sized Planets Ever Found





Credit: NASA/JPL

ExEP's role: Supported PI, Spitzer, & HQ to develop materials for the public release. Set up dedicated site https://exoplanets.nasa.gov/trappist1/ with original stories, image & video gallery, virtual reality views, travel poster

Trappist media impact: Notes from Felicia Chou, NASA HQ

- The press release & media advisory had more web views than all NASA press releases issued in the last four months of 2016 combined
- Within a few days, the potential reach of all social media posts talking about the announcement was over 3.2 billion non-unique users (includes duplicates who may see multiple posts from different sources)
- Within a few days, 99.97% of all 514,752 social media mentions of the announcement came from non-NASA sources
- #askNASA Q's on social media yielded over 10,000 questions & the scientists answering Q's on Reddit was the top item on Reddit.com on 2/22 afternoon
- On streaming TV, website pageviews and reach of NASA's own social media posts, this was a top 10 NASA story on digital of all time. (7th largest traffic day on NASA.gov since 2013; Top day for reach of NASA's own social media posts since 2015)
- This story has had interest at a level seen only every 18 months-2 years.

Possible New Worlds Exoplanet Telescopes

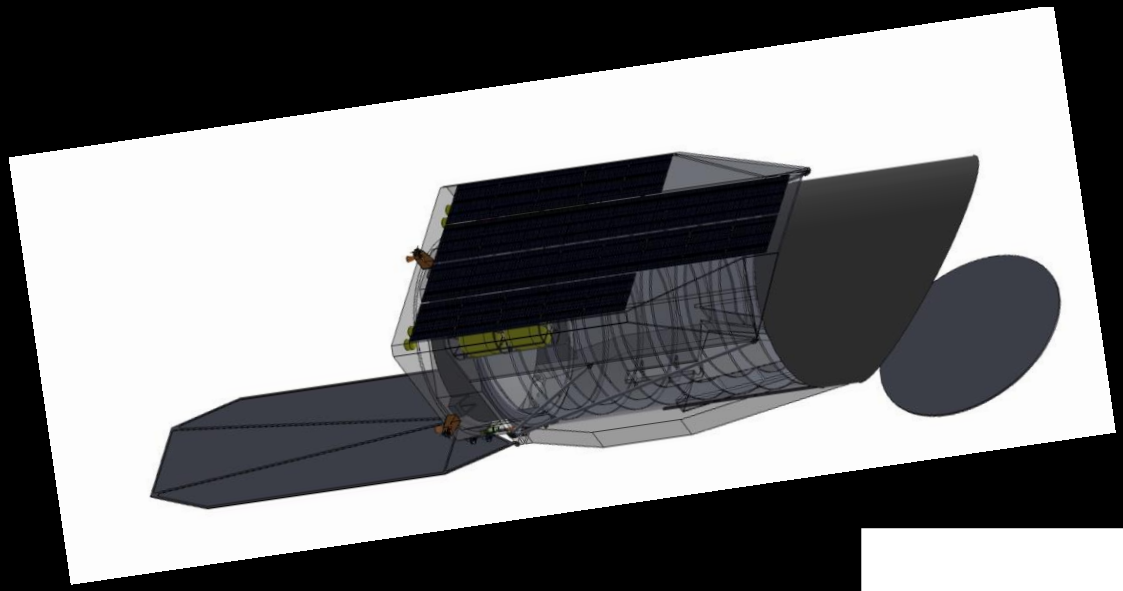
(mid 2030s; work outside ExEP)

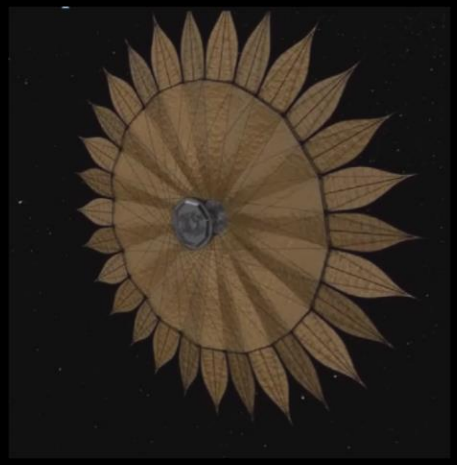
- Origins Space Telescope[1]: mid/far-infrared flagship mission
  - Primary exoplanet science case is transit spectroscopy
  - New exoplanet working group co-Chaired by Lisa Kaltenegger (Cornell) & Kevin Stevenson (STScI)
- Large Ultra-Violet Optical InfraRed Telescope (LUVOIR)[2]
  - Coronagraphic imaging with deployed/segmented primary mirror
  - Large apertures & exoplanet survey samples
  - 5 instruments, equal weighting to exoplanets & general astrophysics
- Habitable Exoplanet Mission (HabEx)[2]
  - Coronagraph & starshade imaging with monolithic, off-axis telescope
  - Smaller apertures & exoplanet survey samples
  - 3 instruments, including UV spectrometer & general astrophysics camera

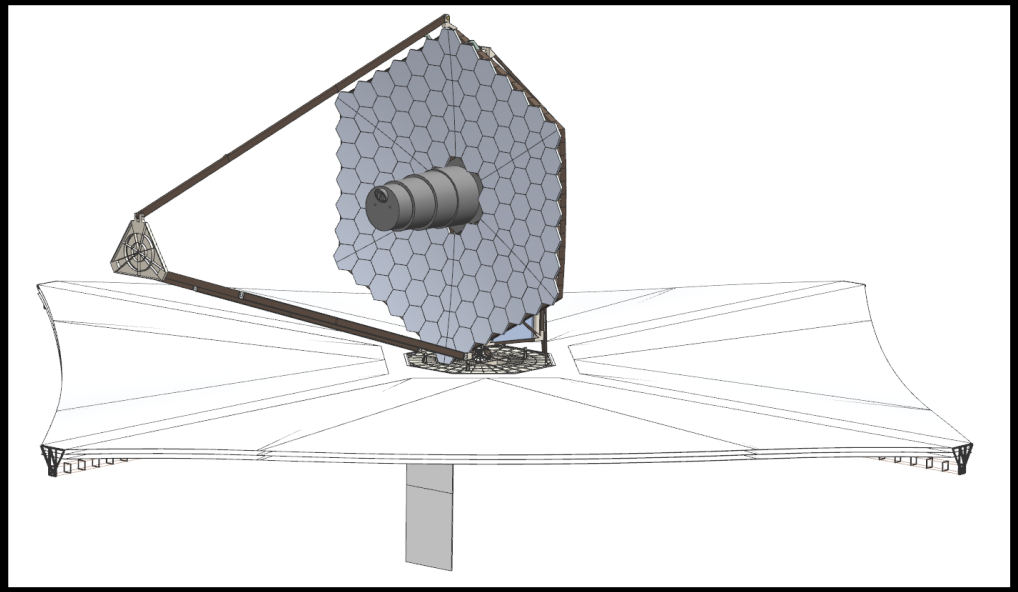
[1]Eric Mamajek, [2]Karl Stapelfeldt track for ExEP

Progress in HabEx and LUVOIR designs

(work outside of ExEP)







Above: HabEx 4m telescope with lateral optical bench, solar pressure paddle & starshade

Right: LUVOIR 15m telescope, 6 ring hex, deployed sunshade

ExEP supports technology needs

Upcoming Program-related Events

- Kepler/K2 SciCon here this week:
  - ExEP Break Out Session Wed 6/21 3:30-5pm.
  - DPCS Eric Mamajek, invited conference talk: “Kepler/K2 in the Context of Future Exoplanet Missions” Fri 6/23 1:30-2pm
- Astronomy in the 2020s: Synergies with WFIRST
  - STScI Baltimore MD, June 26-28, 2017
- Sagan Summer Workshop
  - “Microlensing in the Era of WFIRST”, Aug. 7-11 2017, Pasadena
- 3rd Workshop on Extreme Precision Radial Velocities
  - State College PA, August 14-17 2017
- Know Thy Star, Know Thy Planet – Oct 9-12 2017, Pasadena
- NExSS Workshop “Habitable Worlds 2017”
  - Laramie WY, November 13-17

The Exoplanet Exploration Program

Delivering upon these Purposes:

- Discover planets around other stars
- Characterize their properties
- Identify candidates that could harbor life

Stay connected with us through newsletter and website: exoplanets.nasa.gov/exep

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